

Research Article

Energy modelling of the economic and environmental sustainability of rice farming in southern Brazil

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Abstract

This study presents an emergy-based systems model to analyze the economic and environmental sustainability of rice farming in southern Brazil, with a focus on the states of Santa Catarina and Rio Grande do Sul. Odum's ecological systems theory is at the heart of the model. It measures all flows of energy, matter, and services, whether they are renewable or not, using a single unit called solar emergy joules (seJ). This lets us look at the whole picture. By constructing an energy diagram and calculating critical energy-based sustainability indicators (%R, EYR, EIR, ELR, ESI, EFR), the model quantifies the system's significant dependence on external inputs and underutilization of local ecosystem services. Although the current production model is important for the economy, the results show that it is not very sustainable. It has a very low emergy sustainability index (ESI = 0.26), a very low proportion of renewable sources (%R = 0.15), and a high environmental loading (ELR = 5.73). However, the rice-field landscape has a lot of potential to be used as a Nature-Based Solution if it is managed in more than one way. The results of the modeling efforts offer a solid quantitative foundation for the development of transformative policies, including the recognition of rice fields as multifunctional Green Urban Infrastructure and the implementation of payments for environmental services, in order to promote a more climate-adaptive and resilient agricultural system.

Key words: Agroecology, emergy, ecosystem services, green urban infrastructure, nature-based solutions



Academic editor:

Christopher John Topping

Received: 27 July 2025

Accepted: 5 November 2025

Published: 12 November 2025

Citation: Carvalho-Junior OO, D'Aquino CA (2025) Energy modelling of the economic and environmental sustainability of rice farming in southern Brazil. Food and Ecological Systems Modelling Journal 6: e166845. <https://doi.org/10.3897/fmj.6.166845>

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Introduction

Rice-field landscape has the biophysical capacity to support a strategic role in the regional economy of southern Brazil, with Rio Grande do Sul alone accounting for over 70% of national production through large-scale, highly mechanized irrigated systems (Conab 2025). While Santa Catarina contributes a smaller but significant share with more heterogeneous farm structures, this study focuses on the dominant conventional production model that characterizes the majority of Brazil's rice output. Rio Grande do Sul is the country's largest producer, concentrating the majority of the cultivated area and total output, with highly mechanized and technified systems primarily focused on irrigated rice cultivation in lowland areas. This advanced production structure drives logistical, industrial,

and commercial chains, generating direct and indirect employment and significantly contributing to the region's agricultural GDP. Furthermore, Rio Grande do Sul's rice production is essential for domestic supply and export, positioning the state as a central pillar of national food security.

Globally, agricultural systems are being examined more closely due to their limited social inclusivity and environmental externalities. Despite their recognized role in food security and rural economies, they are still frequently evaluated through narrow productivity or economic lenses that prioritise yield and input–output efficiency (Pretty et al. 2003; Pretty 2007; Bruelle et al. 2015). This reductionist approach systematically disregards the broader ecological, social, and cultural functions that are ingrained in farming landscapes, functions that scholars have long emphasized as essential to long-term resilience and equity (Bruelle et al. 2015).

In response, frameworks such as multifunctional agriculture (Zhang et al. 2007; Renting et al. 2009; Brooks 2014), ecosystem services (Pröbstl-Haider 2015; Costanza 2020), and Nature-Based Solutions (Nesshöver et al. 2017; McPhearson et al. 2022) have arisen to reframe agriculture as a provider of diverse public goods, including flood regulation, biodiversity conservation, climate mitigation, and cultural identity. However, the operationalization of these concepts remains restricted in practice, particularly in fundamental commodity systems such as irrigated rice farming in the Global South, despite the increasing theoretical recognition. Co-benefits, including water purification and habitat provision, are seldom quantified, valued, or incorporated into policy and management decisions, despite their acknowledgment (Norton et al. 2015; Grădinaru et al. 2018). This disconnection between sustainability discourse and on-the-ground agricultural assessment persists.

Limited efforts to transcend narrow productivity metrics persist in irrigated rice systems, particularly in the Global South. Despite growing awareness of the sector's wider ecological role, traditional economic and agronomic assessments of intensive rice production still ignore its biophysical dependencies and hidden environmental costs (Tittonell and Giller 2013; Gliessman 2021). Even though co-benefits like biodiversity support, groundwater recharge, and flood regulation have been recognized by studies (Norton et al. 2015; Grădinaru et al. 2018), these roles are rarely measured, valued, or incorporated into policy or farm-level decision-making. Integrated assessment methods like emergy synthesis offer a promising but underutilized pathway to bridge this gap particularly in fundamental commodity systems such as irrigated rice farming in the Global South. Recent calls to shift from input-intensive systems toward regenerative agriculture, understood as practices that restore ecosystem functions while maintaining productivity (Giller et al. 2021), further highlight the urgency of such integrated assessments. Although emergy has been successfully applied to other agroecosystems, including coffee (Ortega et al. 2005), soy (Cavalett et al. 2006) and dairy (Sun et al. 2023), its use in analyzing irrigated rice, especially in Latin America, remains scarce.

This study addresses this dual gap by applying emergy synthesis to rice field landscapes in southern Brazil, a region of national food security importance yet high environmental pressure. It (1) quantifies energy and material flows, (2) calculates emergy-based sustainability indicators, (3) identifies and contextu-

alizes co-benefits within the GUI and NBS frameworks, and (4) proposes policy pathways to enhance multifunctionality. Combining biophysical accounting and socio-ecological valuation, this work provides a novel, empirically based foundation for transforming rice systems toward sustainability. Through the use of emergy synthesis, the work assesses (a) the biophysical sustainability of the current conventional rice system and (b) the landscape's inherent potential for providing ecosystem services under alternative management paradigms.

Study area and rice production system

The study focuses on irrigated lowland rice farming in southern Brazil, specifically in the states of Rio Grande do Sul (RS) and Santa Catarina (SC), the country's two largest rice-producing regions, which together, account for over 70% of national output (Conab 2025). Rio Grande do Sul is Brazil's leading rice producer, with a highly mechanized and technified production system concentrated in the Western Lowlands and the Guaíba Basin, a vast hydrographic region surrounding the State capital, Porto Alegre. The landscape is characterized by flat or gently undulating topography, hydromorphic soils (predominantly Gleysols and Planosols), and a humid subtropical climate (Köppen Cfa), with annual rainfall of 1,400–1,800 mm and no pronounced dry season. Rice is typically grown in monoculture on large-scale farms (often >100 ha), using continuous flooding irrigation from October to March. The system relies heavily on synthetic inputs: nitrogen, phosphorus, and potassium fertilizers; chemical herbicides and pesticides; and diesel-powered machinery for land preparation, harvesting, and post-harvest processing. Water management is centralized through extensive canal networks and pumping stations, frequently drawing from rivers and reservoirs within the Guaíba hydrological system.

Santa Catarina, while smaller in total production, features a more heterogeneous system, with significant activity in the Araranguá Valley and other coastal lowlands. Here, rice fields are frequently embedded in peri-urban landscapes, adjacent to towns and cities, creating unique socio-ecological interfaces. Farms range from medium-scale commercial operations to smallholder plots, and while still largely conventional, there is growing interest in diversification and multifunctionality (Vale et al. 2022). The same irrigated, monoculture model predominates, but the proximity to urban centers amplifies the potential for co-benefits such as flood mitigation, recreational use, and environmental education.

The typical production cycle analyzed in this study spans one agricultural year (October–March) and includes the following key operations:

1. Land preparation: leveling and puddling of fields using tractors and laser-guided equipment to ensure uniform water depth;
2. Seeding: direct sowing (mostly aerial or mechanical) of high-yielding cultivars;
3. Irrigation: continuous flooding (5–10 cm depth) maintained throughout the vegetative and reproductive stages;
4. Fertilisation and pest control: multiple applications of NPK fertilizers and agrochemicals based on soil testing and pest monitoring;

5. Harvest: mechanized combine harvesting at physiological maturity;
6. Post-harvest: drying, storage, and transport to processing cooperatives or mills.

This input-intensive, high-yield model, while economically productive, places significant pressure on water resources, accelerates soil degradation, and largely overlooks the landscape's potential to deliver valuable ecosystem services.

To capture the characteristics of this dominant system, our emergy analysis is based on a representative 1-hectare module that integrates average technical and management parameters from extension recommendations by Epagri (Santa Catarina) and Emater/Ascar (Rio Grande do Sul), supplemented by field surveys and regional agronomic literature (Vale et al. 2022). Due to its national economic significance and representativeness of the conventional model under analysis, the model is primarily parameterized to reflect the large-scale, input-intensive rice farming system that is common in Rio Grande do Sul, the center of Brazil's rice production, even though the study includes both southern states.

Materials and methods

This study aims to analyze the economic and environmental sustainability of rice farming in southern Brazil, focusing on the states of Santa Catarina and Rio Grande do Sul, using the emergy synthesis methodology. This approach is grounded in ecological systems theory and enables an integrated assessment of natural and economic flows, providing an environmental accounting framework that considers both renewable and non-renewable resources used in the production system.

Emergy analysis is based on the concept of emergy, defined by Odum (1996) as the amount of solar energy (in solar joules, seJ) required, directly or indirectly, to generate a given product or service. Emergy allows for the comparison of inputs of different energy qualities, such as solar radiation, rainfall, fertilisers, labour, and infrastructure, within a common unit, enabling a holistic evaluation of the agricultural system's sustainability (Ortega et al. 2005; Yao et al. 2022). The methodological procedure was divided into three main stages: (1) construction of an energy diagram; (2) development of an emergy accounting spreadsheet, and (3) calculation of emergy-based sustainability indicators.

In the first stage, an energy flow diagram was developed to represent irrigated rice cultivation on a typical 1-hectare plot in Santa Catarina and Rio Grande do Sul. This diagram visually organizes the environmental, economic, and social components of the system, highlighting interactions and energy pathways. It includes local renewable inputs (e.g., solar radiation, rainfall, wind), local non-renewable sources (e.g., soil, groundwater), and purchased inputs (e.g., fertilisers, fuel, electricity, infrastructure, labour, and services). The diagram serves as a structural foundation for the system and guides data collection and organization in the subsequent stage.

The system boundary is defined as a 1-hectare irrigated rice field over one production cycle (October–March). All natural and economic flows crossing this boundary are accounted for as inputs or outputs. Specifically:

- Local renewable sources (R) and local non-renewable sources (N) originate from the immediate environment (e.g., solar radiation, rainfall,

groundwater, topsoil) and are considered external inputs that support the system but are not owned or controlled by the farmer;

- Purchased inputs (P) and services/labor (S) represent economic flows entering the system from the regional/national economy;
- The system output (Y) is the emergy embodied in the harvested rice;
- Ecosystem services (e.g., flood mitigation, groundwater recharge) are not system outputs in the emergy accounting sense; they are externalities that benefit society beyond the farm boundary and are therefore, identified qualitatively, not quantified as seJ flows.

This boundary follows standard emergy practice for agricultural systems (Brown and Ulgiati 2004; Ortega et al. 2005), where the farm is the unit of analysis and externalities are acknowledged but not double-counted as both inputs and outputs.

In the second stage, an emergy accounting spreadsheet was developed, in which all inputs identified in the diagram were quantified annually and converted into solar emergy equivalents (seJ/year). The flows were classified into four categories: local renewable sources (R), local non-renewable sources (N), purchased inputs (P), and services and labor (S). For each input, specific equations from the technical literature were applied, including: calculation of incident solar energy based on annual average insolation and albedo; conversion of chemical and gravitational potential of rainfall; estimation of plant transpiration; quantification of wind energy based on average wind speed; and calculation of soil loss due to erosion, considering factors such as erodibility, topography, and vegetation cover. Additionally, inputs such as nitrogen, phosphorus, potassium, fuel, and electricity were converted to emergy using standard transformity values.

In the third stage, key emergy indicators were calculated to assess system sustainability. Total system output (Y) was calculated as the sum of all inputs: $Y = R + N + P + S$, where R = local renewable sources, N = local non-renewable sources, P = purchased inputs, and S = services and labor. Economic feedback (F), representing flows from the economy, was calculated as $F = P + S$. Based on these values, five key indices were derived: the percentage of renewable sources (%R) indicates the proportion of local renewable resources relative to total inputs; the emergy yield ratio (EYR) expresses the system's ability to harness local resources, calculated as $EYR = Y/F$; the emergy investment ratio (EIR) reflects dependence on external inputs, given by $EIR = F/(R + N)$; the environmental loading ratio (ELR) measures environmental stress, calculated as $ELR = (N + F)/R$; the emergy sustainability index (ESI) combines efficiency and environmental pressure, defined as $ESI = EYR/ELR$; and the emergy footprint ratio (EFR) relates total production to the use of renewable resources, calculated as $EFR = Y/R$.

The conversion from emergy to economic units (emdollars) was performed using the Brazil-specific Emergy-to-Money Ratio (EMR) of $2.81E+12$ seJ/R\$, corresponding to the most recent national emergy synthesis available in the National Environmental Accounting Database (NEAD v2.0) for the reference year 2015 (<http://www.emergy-nead.com/country/data>). This EMR represents the ratio of Brazil's total annual emergy use to its Gross Domestic Product (GDP) in constant 2015 Brazilian Reais and is used to express the non-renewable emdollar cost of inputs and services.

This approach follows the methodology established by Brown and Ulgiati (2004) and applied in previous national emergy assessments (Ortega et al. 2005;

Cavalett et al. 2006). By using Brazil's year-specific Emergy-to-Money Ratio (EMR), we ensure that the non-renewable emdollar (em\$) values accurately reflect the country's economic conditions and purchasing power during the study period. This allows for a meaningful interpretation of the economic burdens and resource intensity associated with rice farming within the broader national economy.

The research area is southern Brazil, with a focus on Santa Catarina and Rio Grande do Sul, the main centers of irrigated rice production in the nation. The rice-field landscape in these regions is deeply ingrained in hydrological processes that are crucial for environmental regulation and has the biophysical capacity to support a strategic role in the regional economy. The emergy analysis is based on a representative 1 hectare module that integrates region-specific biophysical and management data reflective of conventional irrigated rice farming in southern Brazil. Agronomic and management parameters (e.g., seeding rates, fertilizer doses, irrigation volumes, fuel, and electricity use) were primarily based on technical recommendations from Emater/Ascar (Rio Grande do Sul) for large-scale irrigated rice systems. Where RS-specific data were unavailable, we supplemented with Epagri (Santa Catarina) guidelines and national databases (Picoli et al. 2018; IBGE 2019), ensuring alignment with the dominant conventional model in southern Brazil.

Climate and hydrological inputs (solar radiation, rainfall, wind speed, and evapotranspiration) were sourced from INPE (National Institute for Space Research), EMBRAPA (Brazilian Agricultural Research Corporation), FAO (Food and Agriculture Organization) (Allan et al. 1998) and ANA (National Water Agency) (ANA 2023) to calculate renewable environmental flows (e.g., chemical and gravitational potential of rain, wind energy). Soil loss estimates were derived using the Universal Soil Loss Equation (USLE) with data from IBGE (2019) and remote sensing studies (Picoli et al. 2018). Yield and economic benchmarks were cross validated with Conab (2025) and regional literature (Zhang and Ma 2020; Vale et al. 2022). Together, these sources establish the annual emergy, material and service flows that are quantified in the emergy accounting table and serve as the foundation for all sustainability indicators. This guarantees that the model accurately represents the average operational and environmental conditions of the dominant rice production systems in the region.

Transformity values were primarily drawn from Odum (1996) and subsequent updates by Brown and Ulgiati (2004, 2007), as well as regionally validated studies in Brazil (e.g., Ortega et al. 2005; Cavalett et al. 2006; Zhang and Ma 2020). Where possible, transformities were selected to reflect Brazil's energy matrix, particularly for electricity, which benefits from a high share of hydropower. A full list of transformities, sources, and contextual notes is included in Table 1. It is acknowledged that transformity values can carry significant uncertainty (often $\pm 30\text{--}50\%$), particularly for complex inputs like fertilizers or labor; however, the use of consistent, peer-reviewed values ensures comparability with other emergy studies in the region.

Results

In this study, ecosystem services such as flood mitigation, groundwater recharge, and biodiversity support are identified qualitatively as potential co-benefits that accrue to society beyond the farm boundary. Following standard

Table 1. Values of renewable and non-renewable sources, including goods and services presented in Fig. 1. All economic inputs in Table 1 are converted to emergy using the national EMR; the R\$ flows in Fig. 1 serve only illustrative purposes and are not used in calculations.

Note	Item	Renewable fraction	Quantity	Emergy intensity (sej/unit)	References	Total solar emergy (seJ/ano)	Renewable emergy	Non-renewable emergy	Emdollars
Local renewable sources (R)									
1	Solar radiation, J	1	5.32E+22	1.00	NEED				
2	Rain (potential chemical), J	1	7.41E+10	2.35E+04	Zhang and Ma (2020)	1.74E+15	1.74E+15	0.00E+00	6.20E+02
3	Transpiration, J	1	6.42E+19	1.82E+04	Brown and Bardi (2001)	1.17E+15	1.17E+15	0.00E+00	4.16E+02
4	Rain (geopotential), J	1	1.57E+09	1.31E+04	Zhang and Ma (2020)	2.06E+13	2.06E+13	0.00E+00	7.33E+00
5	Wind, J	1	1.06E+09	1.90E+03	Zhang and Ma (2020)	2.02E+12	2.02E+12	0.00E+00	7.18E-01
	Total local renewable sources (R)					2.93E+15	2.93E+15	0.00E+00	1.04E+03
Local non-renewable sources (N)									
6	Net loss of topsoil, J	0.00	2.09E+08	1.24E+05	Brown and Bardi (2001)	2.60E+13	0.00E+00	2.60E+13	9.24E+00
7	Water use, J		9.88E+10	3.53E+04	Zhang and Ma (2020)	3.49E+15	0.00E+00	3.49E+15	1.24E+03
	Total local non-renewable sources (N)					3.51E+15	0.00E+00	3.51E+15	1.25E+03
Acquired inputs (P)									
8	Nitrogen, g	0.05	8.20E+03	4.05E+10	Brandt-Williams (2002)	3.32E+14	1.66E+13	3.15E+14	1.18E+02
9	Phosphorus, g	0.05	2.00E+01	3.70E+10	Brandt-Williams (2002)	7.40E+11	3.70E+10	7.03E+11	2.363-01
10	Potassium, g	0.05	3.53E+06	2.92E+09	Brandt-Williams (2002)	1.03E+16	5.16E+14	9.80E+15	3.67E+03
11	Electricity, J	0.81	9.00E+09	4.50E+05	Cavalett et al. (2006)	1.13E+15	9.11E+14	2.14E+14	4.00E+02
12	Fuel, J	0.05	1.06E+10	1.10E+05	Brandt-Williams (2002)	1.16E+15	5.81E+13	1.10E+15	4.13E+02
	Total inputs purchased (P)					1.29E+16	3.87E+15	1.20E+16	4.60E+03
Services and Labor (S)									
13	Labor, J	0.6	4.71E+07	7.56E+06	Zhang and Ma (2020)	3.56E+14	2.14E+14	1.42E+14	1.27E+02

(1) Solar Radiation, J: Annual Energy = (Mean Annual Total Insolation)(Area)(1-albedo). (2) Chemical Potential Precipitation, J: Annual Energy = (Volume)(Water Density)(Gibbs Free Energy). (3) Transpiration, J: Annual Energy = (Volume, m³)(Water Density, kg/m³)(Gibbs Free Energy, J/kg). (4) Geopotential Rainfall, J: Annual Energy = (Rainfall, m/yr)(Mean Elevation Change, m/km)(Area, m²)(Water Density, kg/m³)(Gravity, m/s²). (5) Wind, J: Annual Energy = (Area)(Density)(Air Drag Coefficient)(Velocity³). (6) Topsoil loss, J: Annual energy = (Organic matter loss)(5.4 kcal/g)(4186 J/kcal). Erosion rate = (R)(K)(LS)(C)(P). Net topsoil loss = Erosion rate)(crop area). Organic matter loss = Net topsoil loss) (0.05). (7) River water, J: Annual energy = (Volume)(Water density) (Gibbs). (8) Nitrogen, g: Annual energy = (Total nitrogen)(% active ingredient) (1009). (9) Phosphorus, g: Annual energy = (Total phosphorus)(% active ingredient) (1009). (10) Potassium, g: Annual energy = (Total potassium)(% active ingredient) (1009). (11) Electricity, J: Annual energy = (kWh/ha/year) (3.60E+06 J/kWh). (12) Fuel, J: Annual energy = (fuel, litres/ha/year) (1.32E + 08). (13) Labour, J: Annual energy = (Consumption kcal/day for 8 hours of work/day) (1 calorie, J/kcal) (individual – hours/ha/year).

emergy methodology (Brown and Ulgiati 2004), the system boundary is limited to the 1-hectare rice field, with rice grain as the primary output. Ecosystem services are not quantified as emergy outputs because their valuation would

require expanding the system to include external beneficiaries (e.g. urban populations) and estimating emergy equivalents of avoided damages or enhanced well-being, data that are beyond the scope of this analysis. Thus, all emergy indicators (e.g., ESI, ELR) reflect internal system performance, while co-benefits are discussed as externalities in the discussion.

Fig. 1 illustrates the rice farming system practiced in southern Brazil, providing a schematic representation of the flows of natural resources, agricultural inputs, production processes, and the resulting environmental and economic impacts of this activity. This representation is essential for understanding the complexity of the rice production chain from an integrated perspective, enabling the identification of key factors that influence its sustainability.

On the left side of the diagram, renewable environmental resources (sun, wind, and rain) are depicted as circular sources, providing foundational energy flows (solid lines) that enter the system's core landscape and water compartments. These natural inputs are supplemented by human-managed inputs, such as seeds and infrastructure (fuel, electricity, fertilizer, pesticide), which

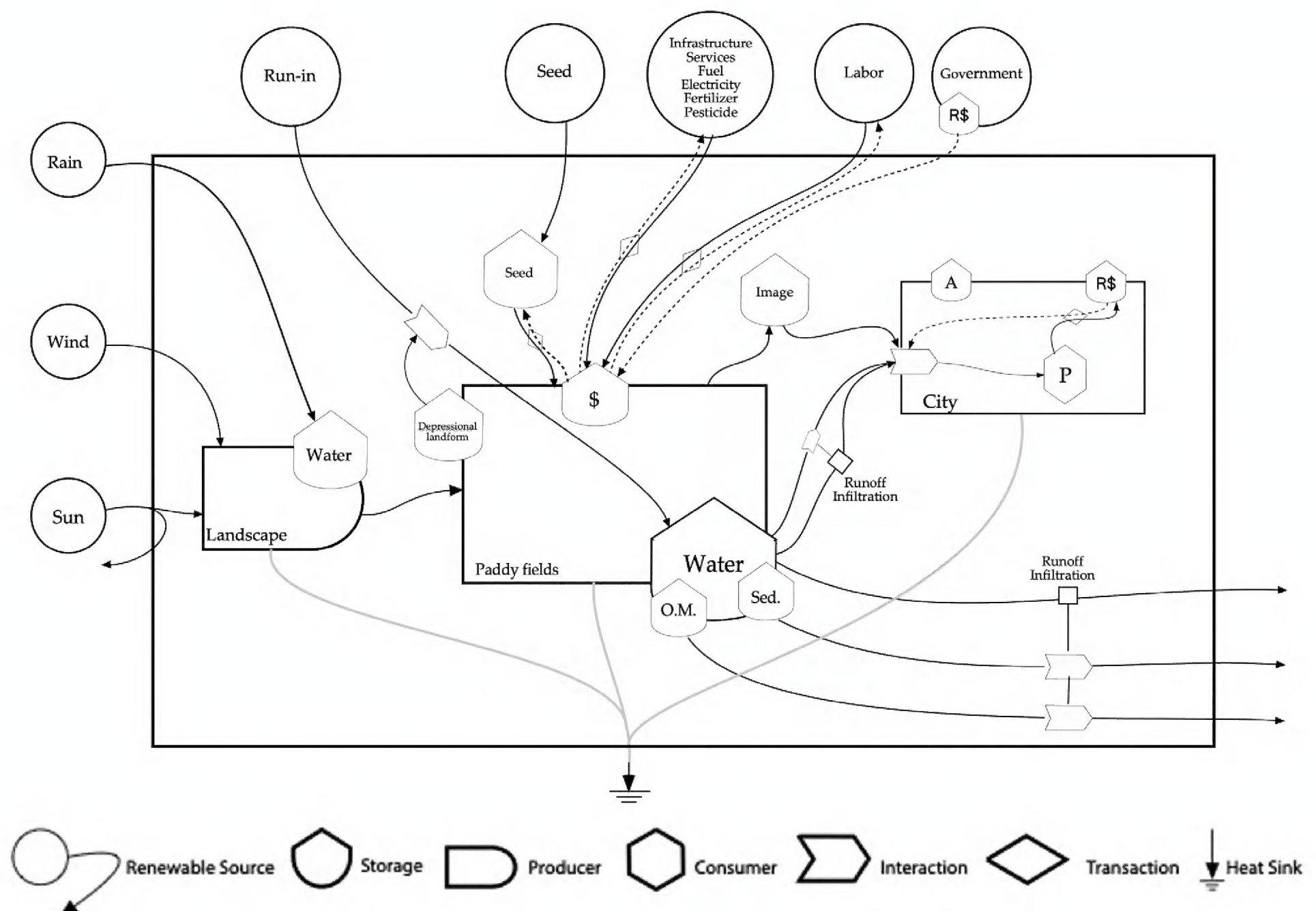


Figure 1. Resource flow and impacts on rice farming in southern Brazil. The system boundary encompasses the 1-ha rice field. All flows crossing this boundary are accounted for as inputs (left) or societal interactions (right-above). The 'Image' and ecosystem service arrows represent qualitative externalities, not quantified emergy flows. The 'Image' storage is a conceptual output representing societal perception; it is not quantified in seJ and does not represent a physical energy stock. The water pentagon, which is located within the system in the paddy fields, serves as a temporary storage system for irrigation and rainfall within the 1-hectare system during the production cycle. Sed = sediment; O.M. = organic matter; A = environmental or economic assets; R\$ = money; P = people. Solid lines represent direct material or energy flows, while dashed lines indicate indirect or financial/economic flows.

also enter via solid lines, representing material and energy flows directed toward the central paddy fields. In parallel, dashed lines represent monetary flows (R\$), flowing in the opposite direction, from the economic system (labor, government, city) back to the inputs, symbolizing financial investment and subsidies that drive the production process.

The diagram uses distinct shapes to classify components: circles denote external source inputs; pentagons represent internal storages or key system components like Water, Seed, Image, and O.M. (Organic Matter); rectangles signify functional areas such as Landscape and City; and diamonds indicate transformation points for runoff and infiltration. The system's outputs, including sedimentation, runoff, and the public image of rice farming, flow towards the right, with the "city" compartment capturing both economic returns (R\$) and societal benefits, thereby completing the cycle of resource use, economic exchange, and environmental impact.

The diagram also highlights the core production processes, emphasizing the landscape and water availability, key factors for irrigated rice cultivation. Water is depicted in its various forms of movement, including soil infiltration and surface runoff, and is directly linked to the maintenance of optimal conditions for plant development. The rice field (paddy) is positioned at the center of the productive system, where cultivation takes place, supported by a depression landform that facilitates water retention.

Dashed arrows represent monetary flows (R\$), which are not energy flows but feedback signals from the economic system. In emergy systems diagrams (Odum 1996; Brown and Ulgiati 2004), money is conventionally shown as dashed-line feedback that acts as an engine to mobilize purchased energy and material inputs (fertilizers, fuel, labor). These monetary flows are converted to emergy equivalents (seJ) using the national Emergy-to-Money Ratio (EMR) for quantitative analysis (Table 1) but are shown separately in the diagram to highlight their role in activating economic inputs.

In accordance with standard emergy diagramming conventions (Odum 1996), monetary flows (R\$) are represented by dashed lines to indicate that money itself is not an energy carrier but functions as a feedback mechanism that 'pumps' or enhances the flow of real energy and materials from the economy into the agricultural system. This distinction emphasizes that while money has no intrinsic energy, it commands embodied energy (emergy) through market transactions.

In the presented diagram, the storage symbol associated with "Image" is located on the right-hand side of the rice farming system. This storage symbol indicates that the public image of rice farming is one of the system's key outputs, reflecting the social and environmental perception of the agricultural activity. The "Image" compartment is connected to the central core of the system, the rice field, by an arrow flowing into it, suggesting that production and associated processes directly influence the public perception of the activity. Furthermore, the "Image" stock is also linked to other system components, such as the "City," indicating that the perception of rice-field landscape has the biophysical capacity to support and impact the urban economy and society at large.

While standard emergy diagrams restrict storages to physical energy/matter stocks, we include "Image" as a symbolic representation of the system's social legitimacy and public perception, a non-material but influential output that

shapes policy support and market acceptance. This aligns with recent calls to expand emergy-based systems thinking to include sociocultural feedback (Brown and Campbell 2007; Ulgiati and Brown 2019), though it is not assigned an emergy value.

The strategic placement of the “Image” stock in the diagram underscores the importance of public perception in rice farming, demonstrating that the activity is capable of delivering not only agricultural commodities but also plays a significant role in shaping the public narrative, either positive or negative. This perception can influence political support, social acceptance, and even the economic valuation of rice production, reinforcing its relevance at both local and regional levels. To support and sustain the activity, the sector receives subsidies from the Federal Government, which aim to incentivize production and ensure its continuity. To support and sustain the activity, the sector receives federal subsidies through key policy instruments, including the Plano Safra, which allocated R\$ 516.2 billion to agriculture in 2025/2026 and the ‘Arroz da Gente’ program (Secretaria de Comunicação Social 2024), which has the potential to support low-interest credit and technical assistance to family rice farmers (Secom 2025).

Table 1 presents the annual emergy values (in seJ/year) for each input in the irrigated rice production system, categorized as local renewable sources (R), local non-renewable sources (N), purchased inputs (P), and services and Labor (S). The analysis is based on emergy synthesis, accounting for both natural flows and human-made economic inputs involved in rice cultivation.

Local renewable sources are natural resources that are continuously regenerated by the environment. Key components include rainfall (chemical potential) that represents the chemical energy stored in precipitation, with an emergy value of $1.74\text{E}+15$ seJ/year. Transpiration refers to water loss from plants, contributing $1.17\text{E}+15$ seJ/year. Rainfall (gravitational potential) indicates the energy associated with water flow due to gravity, amounting to $2.06\text{E}+13$ seJ/year. Wind contributes $2.02\text{E}+12$ seJ/year. The total emergy from local renewable sources is $2.93\text{E}+15$ seJ/year, with the majority derived from rainfall (chemical potential) and transpiration.

It is important to highlight that in emergy accounting, solar radiation is not ignored. It is the reference baseline (transformity = 1 seJ/J) against which all other energy forms are evaluated. However, in many agricultural emergy studies, including this one, it is excluded from the total emergy sum (U or Y) to avoid overestimating the system’s apparent scale, as solar energy is abundant, free, and not a limiting factor in most terrestrial systems. Including it would dominate the total emergy value numerically, masking the relative contributions and environmental pressures caused by purchased and non-renewable inputs (e.g., fertilisers, fuel, irrigation), which are the focus of sustainability assessment. This practice follows established emergy methodology (Odum 1996; Brown and Ulgiati 2004), where the emphasis is on embodied energy from human-driven and non-renewable sources that drive environmental loading and economic cost.

Local non-renewable sources are finite resources or those with very long regeneration times. The main inputs in this category include water use, related to irrigation consumption, with an emergy value of $3.49\text{E}+15$ seJ/year and net surface soil loss, representing soil erosion, with an emergy value of $2.60\text{E}+13$ seJ/year. The total emergy from local non-renewable sources is

3.51E+15 seJ/year, highlighting the significant role of water as an essential resource for rice cultivation.

This high emergy value for water use, despite being classified as a local non-renewable flow, underscores the system's high dependence on a resource that is physically renewable but functionally non-renewable within the context of the production cycle due to its intensive and consumptive use. The inclusion of soil loss further emphasizes the environmental cost of land degradation, indicating that the system is depleting its natural capital, which can compromise long-term productivity and sustainability.

Purchased inputs correspond to external resources acquired for cultivation, such as fertilizers, fuels, electricity, and other materials. The main items include nitrogen, with an emergy value of 3.32E+14 seJ/year; phosphorus, with 7.40E+11 seJ/year; potassium, with 1.03E+16 seJ/year; electricity, with 4.05E+15 seJ/year; and fuel, with 1.16E+15 seJ/year. The total emergy of purchased inputs amounts to 1.29E+16 seJ/year, highlighting the significant role these external resources play in the system's sustainability. Services and labor represent the human contribution and the environmental benefits generated by the cultivation process, encompassing both direct agricultural labor and ecosystem services provided by the production system. Labor represents human energy imported into the system via wages and is accounted for as an external service flow, with an emergy value of 3.56E+14 seJ/year.

The local renewable sources include solar radiation, rain (potential chemical), transpiration, rain (geopotential), and wind. These resources are entirely renewable, as indicated by their renewable fraction values of 1.00. Despite their significant total solar emergy contributions, such as rain at 1.74E+15 seJ/unit, all these resources have zero non-renewable emdollars. This reflects that they do not incur any economic cost related to non-renewable energy inputs. However, their economic value is indirectly captured through the emdollars column, which shows substantial values for each resource. These values highlight the significant economic importance of natural resources, even though they are free from non-renewable costs.

On the other hand, local non-renewable sources include net loss of topsoil and water use. Topsoil loss is an exported waste flow, representing depletion of natural capital. It is treated as a non-renewable input cost in energy accounting, although it is an output. Soil is used as a resource by the system (Cavalett et al. 2006). These resources are finite or slowly regenerating, as indicated by their renewable fraction values of 0. The economic significance of these items is highlighted by the non-renewable emdollars, which include a net loss of topsoil of 9.24E+00 emdollars and water use of 1.24E+03 emdollars. Water use stands out as the most economically valuable non-renewable source, reflecting its critical role in irrigation and overall production. The high economic cost of water use underscores the system's dependence on this finite resource, despite it being classified as non-renewable.

Acquired inputs consist of purchased resources such as nitrogen, phosphorus, potassium, electricity, and fuel. Although these inputs are indispensable for productivity improvement, they incur substantial economic expenses, as evidenced by their non-renewable emdollar values: nitrogen (1.18E+02 emdollars), phosphorus (2.63E-01 emdollars), potassium (3.67E+03 emdollars), electricity (4.00E+02 emdollars), and fuel (4.13E+02 emdollars). Among these, potassium

has the highest economic cost, followed by electricity. This highlights the system's heavy reliance on external, non-renewable inputs, particularly fertilizers and energy sources, which significantly contribute to the overall economic burden.

Labor is included under this category, with a renewable fraction of 0.6. Its non-renewable emdollar value is $1.27\text{E}+02$ emdollars, indicating a moderate economic contribution. While labor does not directly represent a non-renewable resource, its inclusion here reflects the human effort required to manage and operate the system, contributing to both productivity and economic sustainability.

As is evident, renewable sources (e.g., solar radiation, rainfall, transpiration, wind) have negligible non-renewable emdollars, underscoring their sustainability. Conversely, non-renewable sources (e.g., soil loss, water use) and acquired inputs (e.g., fertilizers, electricity, fuel) dominate the economic landscape, suggesting a high reliance on external and finite resources. Acquired inputs (fertilizers, electricity, and fuel) account for the highest economic costs, totaling $4.60\text{E}+03$ emdollars, reflecting the system's heavy reliance on purchased materials and energy. Local non-renewable sources (soil loss, water use) also contribute significantly, with a total of $1.25\text{E}+03$ emdollars.

Potassium fertilizers stand out as the most expensive acquired input ($3.67\text{E}+03$ emdollars), followed by electricity ($1.44\text{E}+03$ emdollars) and water use ($1.24\text{E}+03$ emdollars). These findings highlight areas where interventions could reduce economic and environmental costs, such as improving fertilizers efficiency, optimizing water management, and adopting renewable energy sources. The analysis reveals a clear pattern of high economic dependence on non-renewable and purchased inputs, which contrasts sharply with the negligible economic cost of renewable resources. This imbalance underscores the need for strategies to enhance the system's sustainability by increasing the use of renewable resources, reducing soil and water degradation, and minimizing reliance on external inputs. By focusing on these areas, the rice-field landscape has the biophysical capacity to support and achieve greater resilience and economic viability while reducing its environmental footprint.

Table 1 demonstrates that rainfall (chemical and geopotential) is the primary energy source in the system, accounting for about 60% of the total solar emergy used. This highlights the fundamental dependence of rice cultivation on natural water resources. Additionally, significant contributions come from other sources, such as wind, fertilizers, fuel, electricity, and labor, collectively reflecting the integration of natural and human inputs in the production process. Surface soil loss is also identified as a relevant non-renewable flow, although its contribution is relatively small compared to other inputs, indicating an environmental impact that could be mitigated through conservation practices. These data provide a clear overview of energy flows in the irrigated rice production system, enabling an assessment of its energetic and environmental sustainability and informing more efficient and sustainable management policies.

Table 2 presents the results of the emergy analysis of the rice production system in southern Brazil, based on emergy indicators calculated to evaluate the economic and environmental sustainability of the activity. The data reflect the system's performance in terms of renewable and non-renewable resource use, as well as the interaction between the economy and the environment (Ortega et al. 2002, 2005; Cavalett et al. 2006). Local renewable sources (R) include energies derived from naturally regenerated resources such as solar radiation,

Table 2. Energy indicators are calculated to assess the economic and environmental sustainability of rice farming in southern Brazil.

R	Local Renewable Sources	R	2.93E+17
N	Local Non-renewable	N	3.5 1E+15
I	Nature contribution	I=R+N	6.45E+ 15
P	Purchased Inputs (P)	P	1.29E+16
S	Services and Labor (S)	S	3.56E+ 14
y	Yeld (Y)	Y=R+N+P+S	1.97E+ 16
F	Feedback from economy (F)	F=P+S	1.33E+16
U	Embodied emergy	U=I+F	1.97E+ 16
%R	Renewable Percentage	R/(R+N+F)	0.15
EYR	Emergy Yield Ratio (EYR)	EYR Y/F	1.49
EIR	Emergy Investment Ratio	EIR=F/(R+N)	2.06
ELR	Environmental Loading Ratio	ELR=(F+N)/R	5.73
ESI	Sustainability Index	ESI=EYR/ELR	0.26
EFR	Emergy Footprint Ratio (EFR)	EFR=Y/R	6.73
M	Materials	M=M _R +M _N	1.44E+16
M _R	Renewable materials and energy	Natural origin	2.93E+15
M _N	Nonrenewable materials and energy	Minerals, chemicals, electricity, fuel	1.14E+16
ES	Ecosystem services total	Water, agriculture	7.36E+ 13

rainfall, and wind. Their total emergy is 2.93E+15 seJ/year, representing a small fraction of the total emergy used. This indicates a low reliance on sustainable natural flows and reinforces the system’s vulnerability to resource scarcity and climate change.

Local non-renewable sources (N) include finite resources or those with long regeneration times, such as soil, surface water, and mineral materials. Their total emergy is 3.51E+15 seJ/year, highlighting the system’s high dependence on non-renewable inputs. The total natural contribution (I = R + N) is the sum of local renewable and non-renewable sources, amounting to 6.45E+15 seJ/ year, representing the direct contribution of nature to the production system. Purchased inputs (P) refer to external resources acquired for cultivation, such as fertilizers, fuels, and electricity, with a total emergy of 1.29E+16 seJ/year. Services and labor (S) represent the human contribution to the system, including labor and other services, with a total emergy of 3.56E+14 seJ/year. System yield (Y = R + N + P + S) represents the total emergy output of the system, summing all input flows, and totals 1.97E+16 seJ/year. Economic feedback (F = P + S) reflects the flows of economic return to the system, including purchased inputs and services, and amounts to 1.33E+16 seJ/year.

The emergy indicators provide a detailed assessment of the system’s sustainability. The emergy yield ratio (EYR = Y/F) is calculated as the ratio between total system output (Y) and economic feedback (F), yielding a value of 1.49. This indicates a low capacity to harness local natural resources, suggesting a strong dependence on external inputs. The emergy investment ratio (EIR = F/(R+N)) measures the system’s reliance on non-local resources; the calculated value of 2.06 reflects a moderate dependence on purchased inputs. The environmental loading ratio (ELR = (F+N)/R) evaluates the environmental stress imposed by

the system. With a value of 5.73, the ELR indicates a high impact on local renewable resources. The emergy sustainability index ($ESI = EYR/ELR$) combines energy yield and environmental stress to assess overall sustainability.

The resulting value of 0.26 indicates low system sustainability. The emergy footprint ratio ($EFR = Y/R$) relates total output to the consumption of local renewable sources. A value of 6.73 shows that the system consumes significantly more emergy than the renewable resources available locally. An EFR of 6.73 indicates that the current rice system generates nearly seven times more emergy output than can be supported by local renewable flows alone, reflecting a high degree of externalization and ecological overshoot. By comparison, agroecological rice systems in Asia report EFR values below 3 (Liu et al. 2018), suggesting that a significant reduction in purchased inputs, through practices like legume intercropping, alternate wetting and drying, and organic nutrient cycling, could bring southern Brazilian rice closer to a sustainable footprint.

Materials ($M = MR + MN$) represent the total material flows within the system, encompassing both renewable and non-renewable components. The total emergy value is $1.44E+16$ seJ/year. Renewable materials and energy (MR) correspond to locally available natural resources such as rainfall, wind, and solar radiation, amounting to $2.93E+15$ seJ/year. Non-renewable materials and energy (MN) include finite resources such as minerals, chemicals, electricity, and fuels, totaling $1.14E+16$ seJ/year, highlighting the system's high dependence on non-renewable and imported resources.

The percentage of local renewable sources (%R) is extremely low (only 0.15), indicating that the system relies predominantly on external and non-renewable inputs. This reduces its resilience to climate change and resource scarcity. The EYR value of 1.49 suggests low efficiency in utilizing local natural resources, confirming a high dependence on external inputs. The EIR value of 2.06 indicates significant reliance on purchased inputs, although this dependence is moderate, reinforcing the need for greater integration and internal recycling of resources. The high ELR value of 5.73 demonstrates substantial environmental stress, particularly due to the exploitation of non-renewable resources and the overall impact on the ecosystem. The emergy sustainability index ($ESI = 0.26$) is very low, indicating that the current system is not sustainable in the long term. Measures are needed to improve energy efficiency and reduce environmental impacts.

Fig. 2 presents a simplified emergy flow diagram illustrating the rice farming system in southern Brazil, focusing on a 1-hectare lowland area. The central component of the diagram is the "Rice farming" box, which represents the core production process. Natural resources ($R + N$), quantified at $6.45E+15$ seJ, enter the system from the left, serving as the primary inputs for cultivation. These resources include both renewable and non-renewable local sources essential for sustaining the rice farming activity.

At the center of the diagram is rice cultivation, represented by a large green rectangle-with-one-curved-end labeled "Rice farming". This indicates that the productive system is centered on rice farming conducted on a 1-hectare plain. All values in the diagram are expressed in solar emergy joules (seJ), as specified in the bottom legend.

The total emergy used (U) represents the overall energy consumed by the system throughout the production cycle. Its value is $1.97E+16$ seJ, indicating

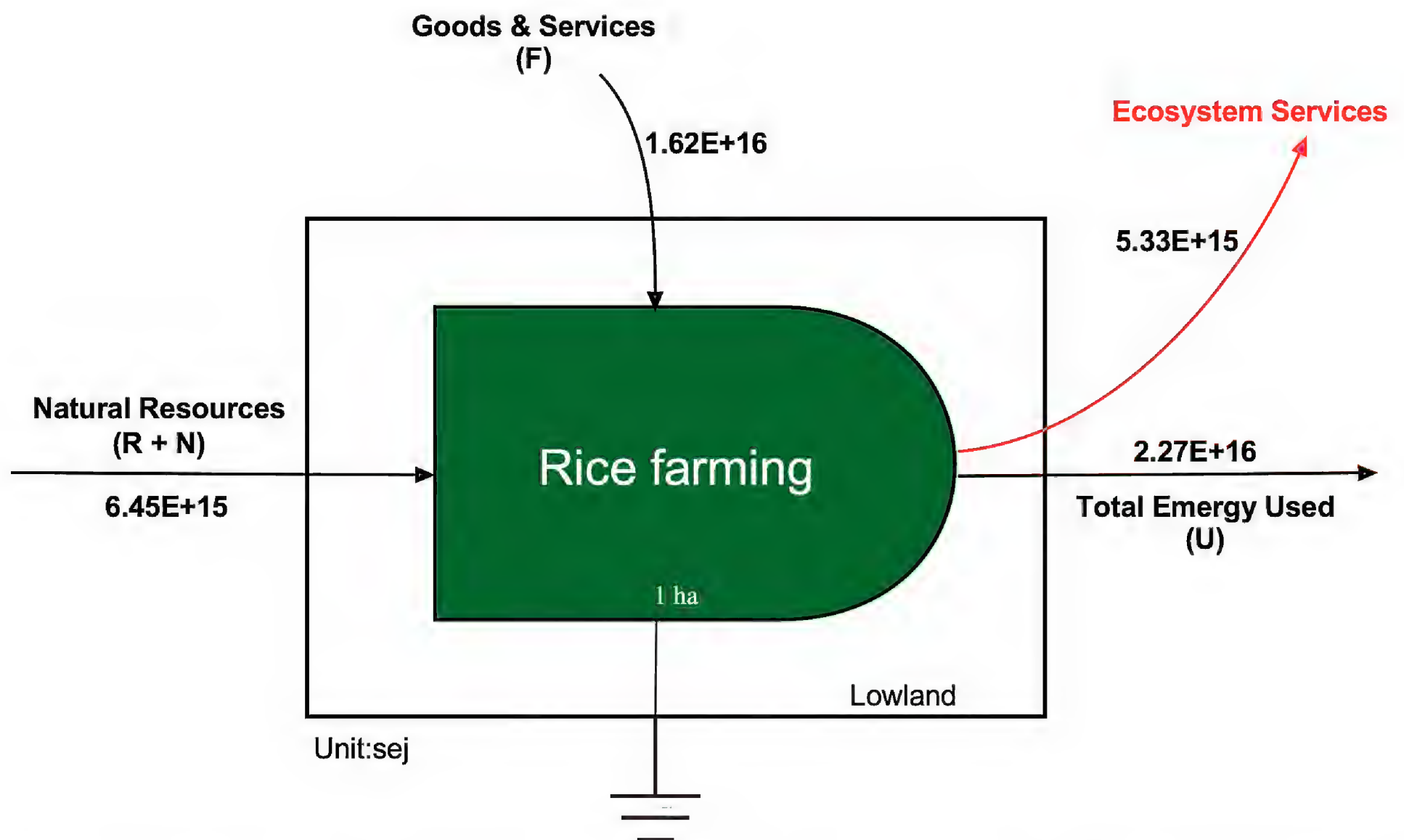


Figure 2. Simplified diagram illustrating the energy flow in the rice production system on a 1-hectare basis, based on emergy analysis. Solid arrows represent quantified energy flows (seJ); the red arrow symbolically represents latent ecosystem service potential inherent to the rice-field landscape, which is not currently activated under conventional management and, thus, not quantified as energy flows.

the amount of energy required to sustain rice cultivation. While rice farming can generate valuable co-benefits, such as flood regulation, groundwater recharge, water purification, and biodiversity conservation, these ecosystem services are not directly quantified as emergy outputs in this analysis. The red arrow in Fig. 2 symbolizes this multifunctional potential, but it does not correspond to a calculated emergy flow. Instead, these services are identified qualitatively and reflect functions that contribute to society beyond the farm boundary, which standard emergy accounting does not capture as system outputs.

Fig. 2 clearly shows that natural resources (R + N) and goods and services (F) are essential inputs for the functioning of the rice cultivation system. Rice cultivation processes these inputs, generating both the total emergy used (U) and ecosystem services. The output of total emergy used exceeds the input of natural resources, reflecting the incorporation of external inputs (goods and services). Ecosystem services represent the potential of rice cultivation to provide environmental benefits beyond agricultural production. All values are expressed in solar emergy joules (seJ), allowing for the comparison of different types of resources and energy flows on a common basis.

The diagram highlights the complexity of the rice cultivation productive system, illustrating how natural resources and external inputs are transformed into total emergy used and ecosystem services. While rice cultivation is capable of delivering considerable environmental benefits, the high total emergy consumption suggests a strong dependence on external resources, which may compromise its long-term sustainability. Fig. 2 also emphasizes the im-

portance of considering ecosystem services as an integral component of the system, recognizing the multifunctional role of rice cultivation beyond mere food production.

Fig. 3 presents a graph assessing the sustainability of the rice cultivation system in southern Brazil based on four key energy indicators: percent renewable (%R), Energy Yield Ratio (EYR), Environmental Loading Ratio (ELR), and Energy Sustainability Index (ESI). The graph uses a color scale to classify the system into three categories: sustainable system, transitional system, and unsustainable system, according to the respective indicator value ranges. The classification criteria for each indicator are as follows: for %R, unsustainable system (<0.2), transitional system (0.2–0.5), and sustainable system (>0.5); for EYR, unsustainable system (<4), transitional system (4–15), and sustainable system (>15); for ELR, sustainable system (<2), transitional system (2–10), and unsustainable system (>10); and for ESI, unsustainable system (<1), transitional system (1–5), and sustainable system (>5).

The graph is vertically divided into three regions: the upper region, representing the sustainable system, identified by a lighter gray band; the central region, representing the transitional system, identified by a gray band; and the lower region, representing the unsustainable system, identified by a darker gray band. Along the horizontal axis are the four energy indicators: %R (Renewable

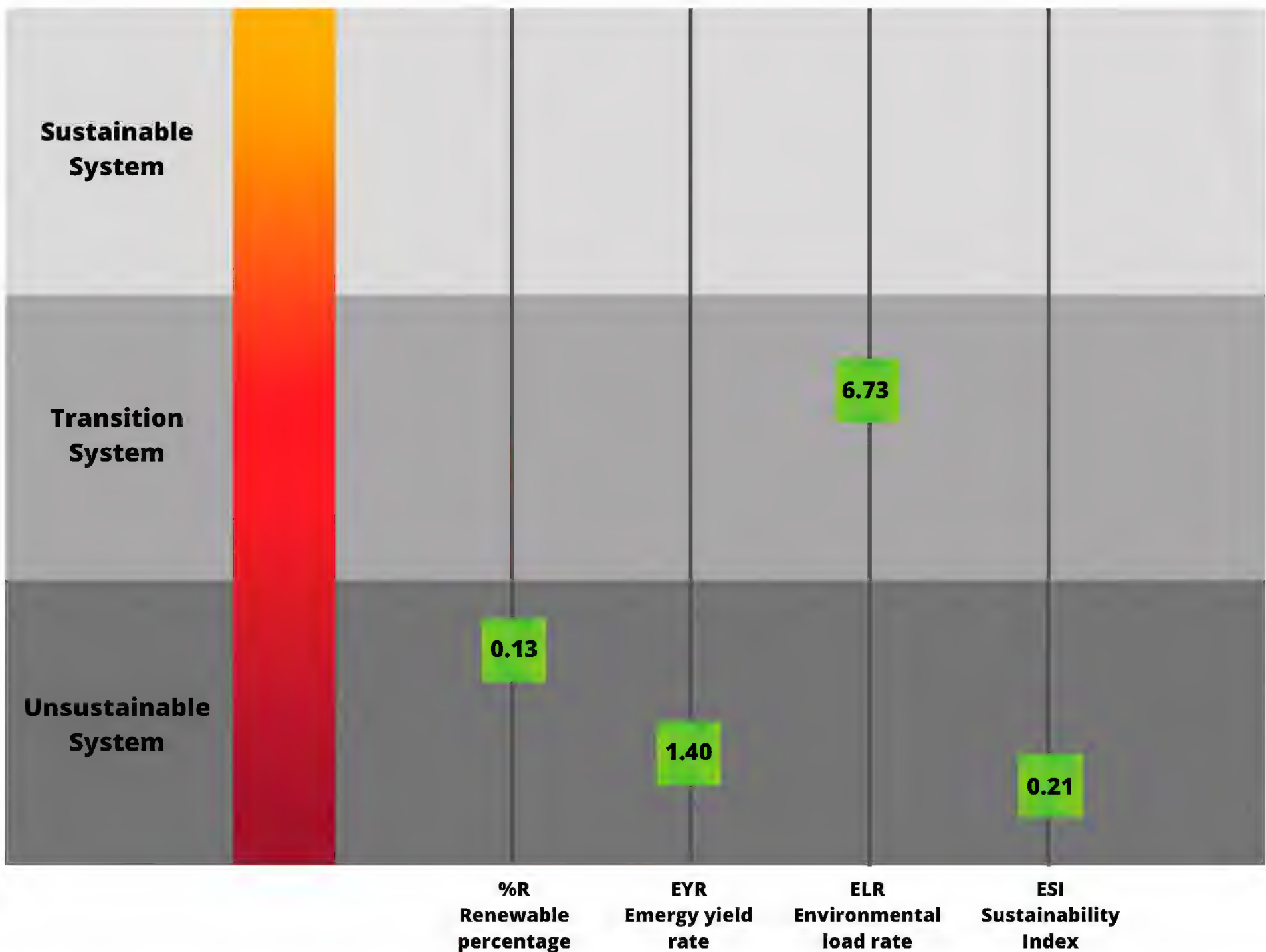


Figure 3. Sustainability of the rice farming system in southern Brazil, based on four energy indicators: Percentage Renewable (%R), Energy Yield Rate (EYR), Environmental Load Rate (ELR) and Sustainability Index (ESI).

Percentage), which measures the proportion of renewable resources used in the system; EYR (Emergy Yield Ratio), which relates the total system output to economic feedback; ELR (Environmental Loading Ratio), which assesses the environmental impact caused by the system; and ESI (Emergy Sustainability Index), which combines the emergy yield ratio with the environmental loading ratio to measure overall sustainability.

For each indicator, specific values obtained from the emergy analysis are presented. The %R value of 0.15 is located in the Unsustainable System region; the EYR value of 1.49 is also in the Unsustainable System region; the ELR value of 5.73 is positioned in the Transitional System region; and the ESI value of 0.26 falls within the Unsustainable System region. The indicator values are compared against predefined criteria to determine the sustainability category. An %R value below 0.2 indicates an unsustainable system. An EYR value below 4 also indicates an unsustainable system. Finally, an ESI value below 1 also indicates an unsustainable system.

The intense red color in the upper regions of the graph highlights that the current indicator values are well below the ranges considered sustainable or transitional. This reinforces the conclusion that the current rice cultivation system in southern Brazil is unsustainable. The specific values (0.15, 1.49, and 0.26) all align with the Unsustainable System category, except 5.73, which aligns with the Transitional System, evidencing low contributions from renewable resources, poor efficiency in utilizing local energy sources, and high environmental stress.

The graph clearly visualizes that the analyzed rice cultivation system falls into the Unsustainable System category for all evaluated emergy indicators, %R, EYR, and ESI, except ELR, which indicates a Transitional System. This reflects excessive dependence on external resources, low efficiency in utilizing renewable energy, and high environmental impact, highlighting the urgent need for interventions to improve system sustainability. The emergy analysis reveals that rice farming in southern Brazil operates with critically low sustainability (ESI = 0.26), driven by extreme dependence on non-renewable inputs, especially potassium fertilizers, electricity, and irrigation water, and a negligible contribution from renewable sources (%R = 0.15). For practitioners, this signals an urgent need to transition toward agroecological management that reduces external input reliance and enhances on-farm ecological functions.

Twelve potential co-benefits of rice cultivation in southern Brazil were identified: environmental education, reduction of habitat loss and fragmentation, biodiversity conservation, tourism and recreation, plant and animal observation, groundwater recharge, microclimate regulation, water purification, air quality improvement, public health enhancement, reduced costs for urban drainage systems, and increased property values in surrounding areas. These 12 co-benefits represent potential functions of the lowland rice landscape that remain largely unrealized under current input-intensive, monocultural management. They are not emergy-quantified outputs of the present system but are inferred from the physical characteristics of the landscape (e.g., water retention capacity, peri-urban location) and evidence from multifunctional agroecosystems elsewhere.

These co-benefits were derived through a systematic and context-sensitive approach that combined a review of peer-reviewed literature on ecosystem services in irrigated lowland agriculture (Norton et al. 2015; Grădinaru et al. 2018),

policy and technical documents from Brazilian institutions such as Epagri and Embrapa (Vale et al. 2022; Embrapa 2025) and direct field observations from technical visits to rice-producing regions in Santa Catarina and Rio Grande do Sul conducted between 2022 and 2024. The triangulation of these diverse sources ensured that the identified co-benefits reflect the specific socio-ecological realities of the region.

The co-benefits identified in this study align with the regulating, supporting, and cultural ecosystem services defined in the Common International Classification of Ecosystem Services—CICES v5.1 (Haines-Young and Potschin-Young 2018). These services were identified through a triangulated, qualitative scoping approach, drawing on peer-reviewed literature, institutional reports (Epagri 2020) and field observations in rice-producing regions of southern Brazil. This method follows established practices in the Nature-Based Solutions (NBS) and Green Urban Infrastructure (GUI) frameworks (Paül and McKenzie 2013; Nesshöver et al. 2017) and is intended to map potential services, not to provide formal biophysical or economic valuation, which would require more detailed modeling and data.

Despite their relevance, these co-benefits remain largely underutilized in current rice farming practices, indicating a significant gap between the system's multifunctional potential and its actual implementation. To bridge this gap and enhance the socio-environmental value of rice landscapes, the study proposes integrating multifunctional strategies such as citizen agriculture (to foster community engagement), leisure farms (to promote rural tourism), natural parks (to support biodiversity preservation), native plant nurseries (to restore local flora), and engineered modifications like increased dike height (to improve flood control and water storage). Such approaches would amplify ecosystem service provision and align rice farming more closely with the principles of Green Urban Infrastructure and Nature-Based Solutions, transforming it into a more resilient and socially inclusive land-use system.

Discussion

The emergy analysis of rice cultivation in southern Brazil reveals a productive system that, despite its economic importance and the multiple ecosystem services it can provide, exhibits low systemic sustainability. This analysis reveals that the largest economic burdens are associated with potassium ($3.67\text{E}+03$ em\$), water use ($1.24\text{E}+03$ em\$), and fuel ($4.13\text{E}+02$ em\$) and electricity ($4.00\text{E}+02$ em\$). These high values indicate that the system's economic sustainability is heavily dependent on finite resources and purchased industrial inputs. The significant emdollar cost of water use, despite being a local non-renewable source, highlights the economic value of irrigation, which is critical for rice cultivation. Similarly, the high emdollar value for potassium, a key fertilizer, underscores the economic cost of soil nutrient depletion and the reliance on external chemical inputs. The cost of fuel and electricity, a major components of the irrigation and processing systems, further emphasizes the system's dependence on non-renewable energy sources.

In contrast, other inputs such as nitrogen ($1.18\text{E}+02$ em\$) and phosphorus ($2.63\text{E}-01$ em\$) have relatively lower emdollar values, suggesting a smaller economic impact from their non-renewable components. The net loss of top-

soil has a minimal emdollar value (9.24), which, while low, still represents an economic cost associated with land degradation. This analysis demonstrates that the system's economic vulnerability is primarily driven by its dependence on high-cost, non-renewable inputs like water, energy, and specific fertilizers. To improve economic sustainability, strategies should focus on reducing reliance on these costly inputs through more efficient water management, the use of renewable energy sources, and the adoption of sustainable soil fertility practices.

The calculated emergy indicators clearly demonstrate an imbalance between agricultural production and the efficient use of local natural resources. The percentage of renewable sources (%R) of only 0.15 indicates excessive dependence on purchased, non-renewable inputs such as fertilizers, fuels, and infrastructure, making the system highly vulnerable to market fluctuations and resource scarcity.

The Emergy Yield Ratio (EYR = 1.49) suggests that, for each unit of emergy from the economy (purchased inputs and labor), the system generates 1.49 units of product. Although this value indicates some capacity to utilize external resources, it is considered moderate and reflects the low contribution of local natural flows. The Environmental Loading Ratio (ELR = 5.73) evidence significant environmental stress, resulting from intense pressure on natural resources, particularly topsoil loss and water consumption for irrigation. This ELR value places the system in a transitional category, according to literature classifications (Brown and Ulgiati 2004; Jung et al. 2018).

The Emergy Sustainability Index (ESI = 0.26) synthesizes these contradictions, confirming that traditional rice cultivation, as currently practiced, is not sustainable in the long term. While emergy indicators enable relative sustainability assessments, cross-study comparisons should account for variations in system definition, transformity sources, and regional baselines (Brown and Ulgiati 2004; Ortega et al. 2005). The ESI of 0.26 is markedly lower than values reported for organic rice systems in Asia (Liu et al. 2018). However, cross-study comparisons in emergy synthesis must be interpreted cautiously due to potential differences in system boundaries, transformity sources, climate contexts, and treatment of co-products. One-digit ESI vs. sub-0.5 ESI strongly suggests that conventional systems that require a lot of input, like those in southern Brazil, are under a lot more environmental stress and depend on outside sources more than their organic counterparts. This is true even if the regional methods are different and the absolute values may not be directly comparable.

The emergy indicators unequivocally show that the current conventional rice system in southern Brazil is ecologically unsustainable (%R = 0.15, ESI = 0.26). However, this does not negate the inherent biophysical potential of the irrigated lowland landscape to deliver regulating and cultural ecosystem services. The flat topography, engineered water control infrastructure, and hydrological connectivity of rice fields, create conditions suitable for flood mitigation, groundwater recharge, and aquatic habitat, functions that are actively suppressed by continuous flooding, agrochemical use, and lack of landscape heterogeneity. Thus, the contradiction dissolves when we distinguish between system performance (what is) and landscape potential (what could be) (Table 3).

This particularly low ESI value derives directly from the combination of a low Emergy Yield Ratio (EYR = 1.49) and a moderately high Environmental Loading Ratio (ELR = 5.73), revealing that the system generates minimal economic

Table 3. Contrasting the current performance of conventional rice farming in southern Brazil with its latent ecosystem service potential under multifunctional management. Indicators on the left derive from emergy analysis (this study); potentials on the right are inferred from landscape characteristics and literature on Nature-Based Solutions.

Dimension	Current Conventional System	Latent Potential (Under Multifunctional Management)
Renewable Input Use	%R = 0.13%	Could increase via green manures, solar drying, etc.
Flood Regulation	Suppressed (continuous flooding)	High (via controlled drainage,buffer zones)
Biodiversity Support	Low (monoculture + agrochemicals)	Moderate-High (with habitat heterogeneity)
Policy Recognition	Treated as commodity crop	Eligible for GUI/NBS incentives

returns at a disproportionately high environmental cost. In contrast to other agricultural systems that have been evaluated through energy synthesis, such as dairy, soybean, or coffee, the irrigated rice system in southern Brazil is distinguished by its extremely high dependence on embodied energy in external inputs, particularly synthetic fertilizers, fuel, electricity, and irrigation water. This heavy dependence on non-renewable and purchased resources not only reinforces its input-intensive character but also highlights its limited resilience and long-term unsustainability within the region’s socio-ecological context.

While this study quantifies the unsustainability of conventional rice farming in southern Brazil, real-world initiatives, such as those led by the Landless Workers’ Movement (MST), show that agroecological, low-input rice systems are not only feasible but already operational in the region. The MST’s organic rice model, which relies on green manuring, biological pest control, and collective land management, offers a tangible alternative that significantly reduces dependence on external inputs. These practices align with the broader framework of regenerative agriculture, defined as farming systems that progressively improve whole-agroecosystem health, including soil, water, and biodiversity, while supporting farmer livelihoods (Giller et al. 2021).

According to emergy theory, such practices would likely increase the share of renewable resources (%R), lower environmental loading (ELR), and thereby improve overall sustainability indicators. However, because these alternative systems were not included in the current emergy assessment, future research should apply the same methodology to MST and similar models to enable rigorous, quantitative comparisons and to guide more effective, evidence-based public investments in sustainable agriculture.

For practitioners, the emergy analysis highlights clear opportunities to reduce dependency on high-cost, non-renewable inputs. In order to reduce the use of synthetic fertilizers, farmers can implement buffer strips or contour dikes, integrate green manures or legume cover crops, and implement alternate wetting and drying irrigation. Moreover, precision agriculture tools, such as UAV-based multispectral imaging and proximal sensing for real-time nitrogen or water stress detection, can support site-specific input management, dramatically reduce fertilizer and pesticide overuse while maintaining yields (Laveglia et al. 2024). For irrigated rice in southern Brazil, such technologies could optimize water and nutrient application in space and time, aligning agroecological goals with operational efficiency. Additionally, they can use water and energy-saving techniques to mitigate soil erosion. Diversifying farm operations through citizen agriculture, agrotourism, or the creation of biodiversity corridors can also increase co-benefits like flood mitigation, habitat connectivity, and recreational value while producing additional revenue.

For policymakers, the results emphasize the need to shift agricultural support systems toward rewarding multifunctionality rather than yield alone. Arroz da Gente and Plano Safra, Brazilian federal programs, could prioritize financial incentives, such as direct payments, technical assistance, and lower-interest credit, for practices that reduce environmental pressure and improve the utilization of renewable resources. These practices include the adoption of bioinputs, investment in water-efficient infrastructure, and organic certification. At municipal and state levels, rice fields in peri-urban areas should be formally recognized as GUI, granting them legal protection and eligibility for Payment for Ecosystem Services. Such mechanisms could compensate farmers for societal benefits they currently provide at no cost, such as groundwater recharge, stormwater retention, and microclimate regulation, thereby internalizing externalities and aligning economic incentives with ecological resilience. Together, these strategies can help transition rice farming from an input-intensive monoculture toward a more diversified, climate-adaptive, and socially inclusive land-use system.

Despite these limitations, the study identifies an underutilized potential of rice cultivation as a Nature-Based Solution (NBS). When well-planned, this activity can perform crucial hydrological regulation functions, flood control, groundwater recharge, water purification, and biodiversity conservation. The list of 12 potential co-benefits, including environmental education, rural tourism, air quality improvement, and increased property values in adjacent areas, demonstrates that the multifunctionality of rice cultivation extends far beyond food production. However, in practice, this multifunctionality is severely limited, with agricultural policies and technologies predominantly focused on maximizing productivity without integrating ecosystem services into the management model.

While emergy synthesis excels at quantifying resource dependencies and production efficiency, it traditionally underrepresents positive externalities such as ecosystem services that accrue to society beyond the farm boundary. In this study, co-benefits are identified qualitatively to highlight multifunctional potential, but their emergy valuation would require expanded system boundaries (e.g., urban flood damage avoided, health benefits from air quality) and additional data, topics for future integrated assessments combining emergy with ES modeling (e.g., InVEST, ARIES).

The low multifunctionality of rice farming in southern Brazil is not derived from emergy ratios themselves but is inferred from the prevailing policy frameworks and on-the-ground management priorities that overwhelmingly emphasize yield maximization and input-intensive production. Emergy analysis quantifies the system's heavy reliance on external, non-renewable inputs and its minimal use of local renewable flows ($\%R = 0.15$), but it does not measure the full spectrum of potential ecosystem services such as flood regulation, groundwater recharge, or cultural value. These co-benefits are identified through qualitative assessment grounded in field observation, technical literature, and policy analysis. Their underutilization reflects a systemic orientation toward monocultural productivity rather than integrated landscape management. Thus, the low multifunctionality is a socio-institutional diagnosis, not a direct output of emergy accounting, underscoring the need for policy reform that recognizes and rewards the broader public goods which rice fields can provide when managed as multifunctional Green Urban Infrastructure.

Beyond environmental and economic flows, rice farming in southern Brazil embeds significant social functions. Field visits and interviews with local technicians revealed that rice fields in peri-urban zones, particularly in the Araranguá Valley (SC) and the Guaíba Basin (RS), serve as informal community spaces, support rural livelihoods for smallholder families, and preserve cultural landscapes tied to regional identity. Moreover, the Landless Workers' Movement (MST) has demonstrated how rice cultivation can be reconfigured as a vehicle for social inclusion, food sovereignty, and collective land stewardship (Pollnow et al. 2020; Lindner and Medeiros 2023). These social dimensions, however, remain largely externalized in conventional productivity-focused assessments and are not captured in standard emergy accounting, which primarily quantifies biophysical and economic flows. Future emergy frameworks could integrate qualitative social indicators (e.g., community participation, labor conditions, cultural value) through mixed methods approaches to better reflect the full societal footprint of agricultural systems.

The proposal to enhance these co-benefits opens pathways for new models of rural and urban development. Practices such as citizen agriculture, leisure farms, natural parks integrated with rice fields, and native plant nurseries can transform rice cultivation into a more inclusive, socially just, and environmentally responsible system. The MST, for example, already demonstrates successful experiences in agroecology and collective land management, promoting food autonomy and environmental conservation. Integrating MST principles with rice cultivation management could drive the transition toward a more sustainable and democratic model.

For instance, the Arroz da Gente program, established by the Federal Government in 2024, constitutes one of the strategic initiatives to promote rice production through family agriculture in Brazil (Secretaria de Comunicação Social 2024). Aimed at stimulating cultivation in different regions of the country and strengthening family production, the program provides rural credit at reduced interest rates for farmers engaged in rice cultivation. Additionally, approximately 10,000 producing families will benefit from specialized technical assistance and financial support for acquiring low-environmental-impact technologies adapted to local socioeconomic and ecological conditions. This public policy represents an effort to enhance family agriculture as an agent of food security, rural development, and productive sustainability.

Conversely, large enterprises linked to rice cultivation have access to significant financial incentives through the Safra Plan, a federal public policy aimed at promoting the agricultural sector. The 2025/2026 edition of the plan allocates a total amount of R\$ 516.2 billion to the agricultural sector, with emphasis on the business segment, including large-scale rice producers. Resources are primarily directed toward rural credit and financing of productive investments, aiming to strengthen the competitiveness of Brazilian agribusiness through modernization, technological innovation, and adoption of sustainable practices.

In this context, the federal government has been promoting the transition to more sustainable production models by offering differentiated interest rates for producers who adopt practices such as organic production, use of bioinputs, and other low-environmental-impact strategies. The plan includes credit lines with special conditions for purposes such as operating costs, marketing, and investment in machinery and infrastructure. Simultaneously, the National

Program for Strengthening Family Agriculture (Pronaf) allocates specific resources to small rural producers, providing access to credit for rice cultivation activities, reinforcing the importance of segmented policies that address different productive profiles within the rice chain.

As system outputs and impacts, Fig. 1 shows the relationship between agricultural production and the urban market, symbolized by the connection between agriculture, financial flow, and final products. Additionally, the environmental effects resulting from intensive resource and input use are highlighted, such as sedimentation, surface runoff, and potential degradation of water resource quality. The public image of rice cultivation is also considered, reflecting the social and environmental perception of the activity. Finally, resource flows are represented by arrows connecting various system components, evidencing interactions between natural, human, and economic factors. This approach allows for a clear visualization of existing impacts and dependencies throughout the productive chain, serving as a basis for analyzing the economic and environmental sustainability of rice cultivation in southern Brazil.

In summary, this discussion reinforces that rice cultivation sustainability cannot be achieved merely through incremental productivity gains. A system reconfiguration is necessary, considering the agricultural landscape as a strategic environmental, economic, and social asset. Emergy synthesis, by quantifying energy flows and their impacts, provides a robust scientific basis for policy decisions that integrate agriculture, conservation, and urban development, aligning with global challenges of climate change adaptation and socio-environmental justice.

Conclusion

Rice farming in southern Brazil plays a vital role in national food security but exhibits critically low sustainability, as shown by emergy indicators: only 0.15% of inputs are renewable (%R), environmental loading is high (ELR = 5.73), and the Emergy Sustainability Index is very low (ESI = 0.26). This reflects extreme dependence on external inputs, especially potassium fertilizers, fuel, electricity, and irrigation water, with minimal use of local ecological functions.

However, the rice-field landscape in southern Brazil possesses substantial latent capacity to provide key ecosystem services, including flood mitigation, groundwater recharge, and biodiversity support, when managed through a multifunctional lens. Shifting toward agroecological strategies such as alternate wetting and drying, organic nutrient cycling, and habitat diversification aligns closely with the regenerative agriculture paradigm, which goes beyond minimizing environmental harm to actively restore degraded ecosystem functions and enhance socio-ecological resilience (Giller et al. 2021).

Formally recognizing rice fields, especially those in peri-urban zones, as Green Urban Infrastructure (GUI) could act as a powerful catalyst for systemic change, integrating agricultural landscapes into urban sustainability planning and governance frameworks. This shift gains further traction when coupled with targeted policy instruments, such as Payments for Ecosystem Services (PES) and inclusive initiatives like Arroz da Gente, and enhanced by digital innovations for precision management. Technologies outlined by Laveglia et al. (2024), including UAV-based monitoring of water and nutrient stress and robot-

ic spot-spraying systems that minimize agrochemical drift and optimize input use, offer practical pathways to reduce environmental loading while maintaining, or even improving, productivity. Together, these synergistic strategies can transform rice farming from a narrow, yield-driven monoculture into a multifunctional pillar of sustainable development, actively advancing climate resilience, ecological regeneration, and social equity across rural–urban continuums.

Acknowledgements

The authors gratefully acknowledge the constructive feedback provided by the reviewers and the editor, which significantly improved the quality of this manuscript. We also acknowledge the use of artificial intelligence (AI) tools to assist in language editing, structural refinement, and literature integration during the revision process. The intellectual content, conceptual framework, data interpretation, and final wording remain the sole responsibility of the authors. No external funding was received for this study.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

Funding

No funding was reported.

Author contributions

Conceptualization: OOCJ. Data curation: OOCJ. Formal analysis: OOCJ. Investigation: OOCJ. Methodology: OOCJ. Writing – original draft: OOCJ. Writing – review and editing: OOCJ.

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Data availability

All of the data that support the findings of this study are available in the main text.

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